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Exploring the role of ICT on household behavioural energy efficiency to mitigate global warming

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ABSTRACT

With the advent of ICT in the energy system, new possibilities to inform and influence residential electricity consumption become available. We explore the potential of ICT-based interventions in households to decrease electricity usage, improve energy efficiency and thus contribute to reducing GHG (greenhouse gas) emissions from this sector. Based on a literature review on the subject, we suggest that ICT can affect some of the main behaviour-influencing factors, and discuss the causal avenues by which these effects can take hold. Our review finds that ICT-based effects on consumer behaviour can reduce household final electricity consumption by 0–5%. These and other findings from the literature are used to define parameter values, which reflect the efficacy of ICT at changing household energy usage patterns, and ultimately decreasing GHG emissions from the electricity sector. A quantitative analysis of the potential for ICT to contribute to reaching the 1.5 °C target in the context of the European Union (EU) energy sector is performed. It is found that ICT-based interventions in household energy use could contribute between 0.23% and 3.3% of the EU CO_2e reduction target from the energy sector that would keep warming under 1.5 °C, corresponding to 4.5–64.7 mio. tCO_2e abated per year.

1. Introduction

Information and communication technologies (ICT) are expected to contribute to the transition to a low-carbon electricity system by making it possible for consumers to make more efficient energy decisions [1]. The central technology in the ICT-energy sphere is the smart meter, which is a part of advanced electricity metering infrastructure that allows for measurement and storage of electricity data at high resolution (i.e. hourly or quarter-hourly) and facilitates near real-time communication of these data to consumers and utility companies. Smart meter technology enables interventions in household electricity usage such as home energy management, battery system management, distributed renewable production management, dynamic (time-variant) electricity tariffs, demand forecasting and load-shifting (demand response) [2]. These measures can optimize and increase efficiency in household electricity use, reduce grid operation costs, and ultimately reduce carbon emissions from electricity production. To increase its effectiveness smart meter infrastructure can be augmented and combined with other ICT-based solutions such as phone and computer applications, automated smart home and smart thermostat systems, and direct communication platforms between utilities and consumers.

The European Union (EU) is at the forefront of adopting ICT in the energy sector, with the goal of equipping 80% of suitable households with smart meters by 2020 [1]. In the past, European households were informed about their electricity consumption only one time per year or per month. The goal of the smart-meter-driven future is that the higher frequency of feedback may support households in adopting energy efficiency and energy conservation measures on a grander scale. It is important to note that while smart meter technology is well-developed, it is still subject to the inaccuracies and 'kinks' of a newer technology. For instance, Leferink et al. [3] show how electromagnetic interference can lead to inaccurate reading from smart meters. This paper takes the view that these issues are not major, and are unlikely to substantially derail the smart meter rollout and its applications.

Abbreviations: CO_2e, carbon dioxide equivalent; CZ, Czech Republic; EC, European Commission; EU, European Union; EU-27, European Union with 27 member states (2007-2013); EU-28, European Union with 28 member states (2013-current); EUR, Euros; GHG, greenhouse gas; Gt, Gigatonne (1 billion metric tonnes); GW, gigawatt (10^9 watts); ICT, information and communication technology; IPCC, Intergovernmental Panel on Climate Change; kWh, kilowatt hour (10^3 watts over a 1-hour period); Mio. T, million metric tonnes; MWh, megawatt hour (10^6 watts over a 1-hour period); SET Plan, Strategic Energy Technology Plan; TWh/a, terawatt (10^{12} watt) hours per year; UK, United Kingdom; U.S., United States of America

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Such increased activities will be needed to meet the challenge of achieving a decarbonised economy and especially actions taken in the building sector which accounts for about 19% of global GHG (greenhouse gas) emissions [4, p 46]. Occupant behaviour in buildings is a major factor influencing the energy-related building performance [5]. People spend more than 90% of their time in buildings [6] and their expected desired comfort level regarding indoor climatic conditions drives them to perform specific actions in order to satisfy their physical and non-physical needs, for example adjusting the thermostat settings, opening windows, or turning on lights [7]. These specific actions directly affect building conditions (e.g. indoor temperature, humidity level, air quality, etc.), thereby impacting energy consumption and energy costs. In total, the effects of these behavioural changes can lead to increases in buildings' actual energy consumption of up to 40% above what could be expected from a purely technical assessment [8].

This paper explores the potential for ICT solutions in the electricity sector to contribute to reducing carbon emissions related to households in order to mitigate global warming. We use the minimal realistic global warming goal of 1.5 °C through 2100 as a benchmark, in light of the ongoing efforts to quantify the impacts of exceeding this goal discussed in the IPCC Special report on Global Warming of 1.5 °C. The 1.5 °C warming goal requires faster uptake of GHG abatement strategies than the 2 °C target [9]. ICT-based interventions could be a means of achieving reduction in GHG from the electricity sector in the near-term, as the investments needed are relatively small on a disaggregated scale (e.g. about 200 EUR for a smart meter per household). To reach the 1.5 °C goal through 2100 total atmospheric CO_2 concentrations should be kept below 430 ppm [4, p 21]. This corresponds to a decrease in anthropogenic GHG emissions of 70–95% by 2050. The EU's Strategic Energy Technology (SET) Plan is in line with this emission reduction target by professing an EU-wide goal of 80% reductions in GHG emissions from the energy sector by 2050 [10]. ICT solutions are expected to contribute to meeting this goal by enabling a "smart consumer-centric energy system" whereby consumers improve the flexibility and efficiency of the energy system by making more informed choices [10].

To successfully engage European citizens with the transition to a low-carbon energy system the provision of information is critical as it can influence personal norms about the environment, shape associated beliefs, and spur pro-environmental actions [11]. In the energy markets, ICT-based solutions can play a pivotal role in providing feedback and making energy flows visible [12]. The more visible information about energy consumption patterns, prices and other related aspects, the more attention it will likely receive from users, making them more aware about the impact of their actions in terms of overall comfort and energy efficiency potentials.[1] The European Commission has repeatedly addressed energy savings through ICT [1,10,13–15] and derives three conditions needed to trigger lasting behavioural change and energy savings, which are:

i. A high level of information and communication
ii. The provision of economic incentives
iii. Supporting administrative frameworks, such as regulated dynamic tariff schemes

The first of these conditions is the core mechanism addressed with consumer information oriented ICT systems. The second channel relies on ICT as well, e.g. by providing households dynamic prices and tariffs incentivizing loadshifting towards times of high production from renewable sources. While such prices and tariffs are not primarily designed to reduce total electricity consumption, their ecological effect is potentially high when they achieve a substitution of fossil electricity generation with renewable generation. The European Environment Agency [5] assessed that behavioural change measures can deliver sustainable savings of between 5% and 20% of total energy demand. These benefits come on top of the energy efficiency improvements that can be achieved by technological measures.

A primary goal of our paper is to assess the potential for ICT driven behavioural change to contribute to reductions in electricity usage and ultimately GHG emissions. Section 2 discusses the theoretical and behavioural avenues through which ICT can influence consumer energy choices. Section 3 then reviews the empirical evidence regarding the effect of ICT on household electricity choice and consumption in pilot tests. The review of empirical studies is used to inform our own quantitative analysis of the potential for ICT-based solutions to reduce GHG emissions from household electricity use in the EU. The findings from our quantitative analysis are then generalized to the global case, and compared with the necessary global GHG emission reductions in order to keep global warming under 1.5 °C. To conclude, we infer from the literature review and our own quantitative analysis the potential for ICT-solutions to contribute to keeping global warming under 1.5 °C.

2. ICT and consumer behaviour

In general, user behaviour related to energy use is influenced by four factors: economic considerations, values, attitudes and norms, and practical aspects of daily life [16]. In order to change energy consumption behaviour, routines and habits need to be changed and users need to be made aware of the consequences of their daily energy use. There are three factors that can be used to encourage lasting behavioural change in consumers [17]:

- **Motivating factors**: individual, internal drivers of behaviour. Such factors are awareness, knowledge, social influence, attitude, perceived capabilities and intention. For people to intentionally change their energy behaviour, they must become aware of their energy use, pay notice to it, and be informed about the consequences. They must then be motivated to use the available information and instruments to control their energy use.
- **Reinforcing factors** are consequences of actions that give individuals positive or negative feedback for continuing their behaviour. Such factors include information about the impacts of past behaviour, feedback of peers, advice, and feedback by powerful actors.
- **Enabling factors** are the external constraints on behaviour. These factors allow new behaviour to be realised.

Considering these three categories of factors we note that ICT-based approaches would be appropriate as motivating and reinforcing factors. ICT can be used to supply feedback on a person's energy consumption, show them benchmarks and usage targets, and reinforce behaviour by showing them their monetary or carbon savings.

Darby [18] and Hargreaves [19] show that providing users real-time data about energy consumption in buildings helps change their behaviour. When energy end-users have an appropriate and understandable reference frame, they are empowered to determine whether their energy consumption is excessive or not. Using timely feedback measures will increase the users' awareness of energy consumption while keeping them motivated. The type of feedback and information provided strongly influences the efficacy of such feedback [20]. A current, productive vein of research is to define the optimal feedback strategy and test its application.

The European Union issued Directives 2009/72/EC, 2009/73/EC, and Directive 2012/27/EC that insist on making smart meters available to the majority of households in the EU by 2020. Smart meters collect the electricity consumption of households in a high frequency (i.e. quarterly or hourly values) and transmit these figures to a data hub. The detailed consumption data may then be forwarded to the consumers, and used to motivate them to save energy by better understanding the impact of their behaviour and related financial benefits [21].

[1] Up to a reasonable saturation point, which has not yet been approached.

Forwarding households their electricity consumption data in and of itself may not be a very effective strategy as it is difficult for consumers to interpret their load profiles and derive conclusions for improving their energy efficiency. This is especially true in cases where new tariff structures are applied, as consumers may have little understanding of how they can optimize their consumption under such tariffs. For instance, in the case of peak demand tariffs[2] research has shown that consumers have only a very basic understanding of the peak demand concept and how it can be used to reduce grid costs and electricity costs in a household [22].

Similarly, while people usually know the number of electric devices they own and the primary generation source of the electricity they use, they have little understanding of the energy consumption from these devices [21]. However, with the ascent of smart phones and mobile internet connections, smart phone and computer apps may provide an accessible platform for triggering energy efficiency by exploiting energy consumption data from smart meters in a motivating and incentivizing manner. Using smart phones and tablets as one-stop platforms for the provision of related information to households is a promising potential for motivating households to improve their energy usage. Such applications can combine energy consumption information with game elements and further motivational mechanisms, such as comparison with other consumers, to trigger lasting behavioural change [23].

Efforts to rollout smart meters and other energy-related ICT products are not without complications. Foremost among them is getting consumers to accept new ICT technology and to use it on a consistent basis [24,25]. In terms of accepting smart technology, Richter and Pollitt [26] study the willingness of consumers to accept smart meter services and contracts, including the necessary sharing of personal data with electricity companies. The authors built a discrete choice experiment that was completed by 1892 UK residents. The results of the experiment shows that generally consumers will demand considerable compensation to participate in smart electricity and automated demand response programs. Pricing strategies to incentivize consumers to participate in smart meter programs and target groups of consumers are explored. In particular, the authors suggest a combination of fixed and transaction-based payments would result in increased acceptance of smart meter programs and that strong data privacy services would reduce the total payments required.

Getting consumers to engage with the ICT product could be accomplished through integration with social networks and gamification of the ICT. The usage of social networks has been found to be highly successful at achieving long-term behavioural change in other fields, such as education and sports [27]. Gamification, the use of game mechanics to drive engagement, is a reinforcing factor that has been shown to encourage targeted behaviours with instant positive feedback [28]. The progression and interaction supplied by gamification has the potential to alter long-term behaviour and motivate electricity consumers [29–31]. However, not everyone is motivated through competition and quantifying actions and assigning virtual rewards can backfire with unintended consequences that lead to an increase in unethical behaviour or reduced motivation [32–34]. Research into user experience and interface design suggests that the more time and effort developers spend on creating, testing and refining the most attractive gaming system for user, the higher the user's motivation to engage with the system will be [35,36]. Further research develops the concept of ‘meaningful gamification’, to separate intrinsic and extrinsic motivation and to develop intrinsically motivating solutions through which the participants can carry out their activity more effectively [37–39]. Where gamification fails to produce results, a disregard for user-centric design and lack of motivating factors may be to blame [40]

[2] Peak demand tariffs are a promising tariff structure for reducing grid costs where consumers are charged based on their maximum usage over a time frame.

Overall, while ICT has proven to be an effective tool at increasing the awareness of households towards energy issues and their ability to make more informed energy choices, the specifics of ICT adaptation to this role are still undergoing intensive research. The challenges of smart technology acceptance, motivating behavioural change, and proper feedback mechanisms are particularly important to overcome in the near future for ICT to be able to contribute substantially to a low-carbon energy system.

3. Effects of ICT on household electricity consumption

We review the literature that has estimated the effects of ICT on household electricity consumption in order to inform our quantification of the potential reduction in GHG emissions from improvements in household energy efficiency. The European Commission has repeatedly addressed energy savings expectations from household use of energy-related ICT [13,14]. Estimates from the European Commission [41] find that household electricity consumption can be reduced by up to 20% from behavioural change including energy efficient appliances. The American Council for an Energy-Efficient-Economy found that total energy savings of 22% were feasible for U.S. households [42]. Herein we discuss how ICT can contribute to realizing these savings, and estimate the contribution that ICT can make based on past literature.

Following The European Commission [13,14], Latiner and Ehrhardt-Martinez [42], and Trotta [43] we define the ways in which energy-related ICT can affect household electricity use as:

1) Behavioural change
   a. Appliance-based energy efficiency improvements
   b. Reducing overall electricity consumption
   c. Shifting electricity loads
2) Directly via home-automation systems that optimize energy use

The first category, behavioural change, takes place when households willingly shift their energy consumption patterns in response to information or benchmarking from an ICT platform. We identify three types of behavioural change: appliance based savings, reduction in total energy consumption, and loadshift (or demand response), where consumers change the times they use energy. The second category encompasses the smart home and smart thermostat concepts, where household electricity use is automatically optimized to satisfy the needs of the household and potentially reducing electricity use.

Under the aegis of behavioural change, households can alter their purchasing decisions to choose energy efficient appliances to replace old appliances. An example of appliance based energy savings is a household upgrading their washer to a more energy efficient model, or replacing light bulbs with more efficient varieties. Previous research has shown that energy efficiency upgrades of these types are much more likely to be applied by households with higher levels of education and income [44,45]. In a comprehensive study of energy savings potentials across the EU-27, Eichhammer et al. [46] estimate the potential for increased energy efficiency in household appliances. We refer to their estimates for the year 2020, as these most-nearly reflect the current situation and are less reliant on their assumptions of future technological progress in appliance technical efficiency. Eichhammer et al. [46] find that household electricity consumption can decrease by 5.8–21.9%, with a middle value of 9.9%, depending on the speed of market uptake and the government policies that are in place.[3] While ICT can be used to motivate households to buy more efficient appliances, not all of the estimated reduction in electricity use would be due to ICT-based effects. To account for this we use only the middle value from Eichhammer et al. [46] of 9.9% and perform sensitivity analysis around our assumption of the proportion of electricity savings that will

[3] See Table 6.6 on page 78 of the Eichhammer et al. [46] Final Report.

Table 1
Parameter values for the potential effect of ICT on household electricity behaviours used in the quantitative assessment.

Estimates:	Behavioural change reduction in total household electricity consumption		Appliance-based reduction in total household electricity consumption	
	Source	Value	Source	Value
Optimistic	[49–52]	5% reduction (combined effect of behavioural change and dynamic tariffs)	Assumed[a] 50% of benefits from ICT	4.95% reduction
Middle	[49]	2% reduction	Assumed[a] 25% of benefits from ICT	2.475% reduction
Pessimistic	[20]	0% reduction	Assumed[a] 10% of benefits from ICT	0.99% reduction
Estimates:	**Household loadshift potential**		**Decrease in CO_2 emissions per unit load-shifted**	
	Source	Value	Source	Value
Optimistic	[54]	17% loadshift from peak to off-peak	Assumed value based on [60]	25%
Middle	Assumed value based on [61]	10% loadshift from peak to off-peak	[59]	10%
Pessimistic	[62]	5% loadshift from peak to off-peak	[54]	0%

Note: Most values are based on empirical research, where field tests have been completed. Values that are defined "assumed" are not directly from empirical evidence, but involve some assumptions based on literature, or simulation models.

[a] Eichhammer et al. [46] estimate that household appliance updates contribute a 9.9% reduction of electricity use in their 2020 "high-policy intensity" scenario. We adjust these values based on an assumed proportion of this decrease that is attributable to ICT.

be due to ICT. We use values of 10%, 25%, and 50%, for this assumption, which leads to values of 4.95%, 2.475%, and 0.99%, which we call our optimistic, middle and pessimistic range of values, respectively, for the potential energy savings from appliances due to ICT-based effects reflected in Table 1. Note that improvements in energy efficiency are subject to a rebound effect since the fact that appliances are now cheaper to operate may lead to more appliance usage by households or increases in other purchases [47]. Though researchers have found that this effect will most likely not negate reduction in electricity demand from energy efficiency, it is likely to decrease the overall effect of energy efficiency investments [48]. Our conservative estimates of the potential energy savings from appliances due to ICT also reflect the possible rebound effect.

The reduction of overall energy consumption from behavioural change attributable to ICT-provided feedback, such as that from in-home smart meters, has garnered significant attention in energy research e.g. [20,49,50]. However, the reduction in energy consumption that can be expected from additional information varies strongly between studies [20]. An empirical review of these results was completed in 2013, and found that the average estimated reduction in household energy use from the provision of energy consumption feedback was 7.4% across the 156 studies surveyed [49]. However, of these 156 studies only 22 were robust to respondent socio-demographic, geographic, and climate differences. The 22 robust studies showed an average energy reduction of 2% due to increased information. A more recent, similarly robust study, conducted in Linz, Austria, showed that providing smart meter users with effective feedback related to their energy consumption reduced energy use by 5% [50]. This effect was attributed to habitual changes including changes in appliance usage. In a separate review of past literature, the authors take a more pessimistic view and argue that there may be no medium to long-term reductions in energy use from ICT-based information provision [20]. Furthermore, the type of feedback and information provided strongly influences the level of energy-use-reduction achieved [20].

Dynamic tariffs supplied via ICT may also decrease overall electricity consumption. Stromback et al. [51] and Hillemacher et al. [52] assessed the effects of semi-dynamic tariffs in large field tests and showed that households saved an additional 2.5% and 2.6% of their baseline energy consumption, in Ireland and Austria respectively. It is not yet clear how dynamic tariffs interact with additional information, for instance if these effects are additive, but for our "optimistic" scenario we assume some additivity and include the effects of dynamic tariffs in the quantification of ICT-driven electricity savings. Current large-scale field tests are underway to assess the interactions between dynamic tariffs and increased consumer information [23].

The potential of ICT-induced loadshifting, or demand response, to reduce carbon emissions from energy production is based on the premise that consumption during periods of high demand will be substituted with consumption during periods of lower demand and higher renewable generation. This would enable systemic energy efficiency to be improved, and would decrease the associated GHG emissions significantly. However, it is unclear if this dynamic will consistently hold true such that loadshifting will decrease carbon emissions from energy use on the aggregate [53,54]. The certain environmental value of loadshifting lies in its ability to enable an electricity grid that relies heavily on renewable generation though balancing intermittent supply with demand [55]. Such effects of loadshifting have been shown to lower consumer electricity bills, and reduce price volatility in electricity markets [56,57]. This is not equivalent to saying that households shifting load to off-peak times in and of itself will reduce carbon emissions, which is the effect we are interested in here.

The direct effect of loadshifting on overall carbon emissions is based on the electricity mix of the regional grid, and particularly the amount of renewables in the grid and when these renewables produce electricity compared to peak electricity usage [58]. As such, there is strong regional heterogeneity in the expected effect of loadshifting on carbon output from the electricity sector. Specifically, regions that have high levels of renewable resources that can be dispatched during off-peak hours can see reductions in annual CO_2 emissions between 0 and 600,000 t per GW demand response dispatched to meet peak load [54]. In the case of South Africa loadshifting was estimated to reduce CO_2 emissions by 91 kg per MWh shifted, which amounts to about a 10% reduction in CO_2 emissions per MWh [59]. Due to the relative abundance of low-carbon electricity sources in Europe we suggest that CO_2 reduction due to loadshift could be higher for this continent. As a high-end, "optimistic" estimate of this potential we assume that every kWh consumed during off-peak periods has 25% of the CO_2 compared to an average kWh of electricity based upon Moomaw et al. [60]. Given the paucity of literature on the effects of loadshifting on carbon output we use a range of informed parameter values and perform a sensitivity analysis to complete our analysis of the CO_2-reduction potential of ICT in the European electricity system.

In terms of the potential for households to shift their electricity loads to off-peak hours and realize this reduction in CO_2 emissions we use a middle value of loadshift potential of 10% of annual energy demand based on the review completed by Moser et al. [61]. The lower end value is 5%, which comes from the study of Nilsson et al. [62], who showed that ICT-based price visuals induced Swedish households to shift demand from peak to off-peak times. Our high-end value for loadshift potential comes from Smith and Brown [54], who use a value of 17% in their analysis of loadshifting and carbon emissions.

The second main category, home automations, are usually designed with the primary target of increasing the household's comfort level. Functionalities frequently address, for example, the automatic

adjustment of sunblinds to the intensity of solar radiation, or the combined dimming of lights, playing of pre-selected music tracks and control of other ambient related equipment through pre-settings. However, home automation systems can effectively support the energy efficiency of a building through controlling the heating system, or synchronizing the electricity consumption with rooftop photovoltaic production. Nevertheless, as comfort usually is the primary motivation for installing home automation, energy savings potentials may lag behind. A combination of home automation systems and a consumer information oriented ICT system, at best as a one-stop system, can increase energy savings through more frequent and comprehensive utilization. In one case, a fully optimized home built specifically to interface with smart home technology achieved energy savings of 37% [63]. In a U.S. study, it was estimated that an optimized smart thermostat can save up to 28% of the electricity normally used for heating and cooling [64]. However, this result was not tested in an application to homes. Similarly, Meyers et al. [65] show that in theory 39% of household energy use is wasted and that this same amount could be saved using ICT-enabled monitoring and control technologies. Finally, Cosar-Jorda et al. [66] use data from 11 UK homes to show that household energy demand could be reduced by 50–70% if all of their potential interventions in household behaviour, retrofits and replacement were applied. However, all of these studies lack currently-implementable solutions that are proven by empirical evidence on a large-scale, making it difficult to assess the potential of ICT-based smart home concepts for contributing to carbon reduction on the aggregate. Current rates of home automation systems are low across Europe,[4] and the effects of home automation are likely to be duplicative of behavioural changes. Thus, we do not include estimates of energy savings to this last category of motivational channels in our quantitative assessment.

Table 1 shows the parameter values that we have pulled from the literature, or assumed based on literature, which will inform our quantitative analysis in the next section. We establish a range of values for each parameter from “optimistic” to “pessimistic” to reflect the uncertainty about the final form and efficacy of ICT applications and some divergent research findings. Our chosen range of parameter values matches the expectations of the EU Commission Smart Grids Taskforce who estimated an expected decrease in energy savings between 0% and 5% across 16 EU nations. These figures include behavioural change and loadshifting effects, but only for the application of smart meters and do not include the potential of other ICT-technologies [1].

4. Quantitative analysis

In this section, we estimate the potential effects of ICT-based interventions on household electricity use and subsequent GHG across the EU-28, expressed as CO_2-equivalent (CO_2e) emissions. We use the EU as an illustrative since, in many ways, the EU is leading the global push for de-carbonization of the energy system. Consequently, much of the research and many of the field tests which explore the role of ICT in influencing consumer electricity choices is based in the EU. We expect that as other nations and regions follow the EU towards a de-carbonized energy system the potential for ICT to aid the transition in these regions will be similar to what has been shown for the EU.

This quantification should be taken as a case study and starting point for the much-needed comprehensive research into the realistic potentials for new technologies to contribute to GHG reduction. As such, it is subject to numerous assumptions and uncertainties discussed in Sections 3 and 4, which are reflected in the sensitivity analysis. The scenario assessed is one where empirically-proven ICT-based interventions in energy are spread to all households and are assumed to be functioning as designed.

We build data on the electricity consumption per household at the country level based on Eurostat data, including total household electricity consumption (code tsdpc310), population (code demo_pjan), and average persons per household (code ilc_lvph01). Data from the year 2015 was used, as it is the most recent data with no missing values. We use a static baseline situation where climate variables and technological progress are assumed to remain constant, due to the potentially impactful assumptions required for building dynamic baselines [68]. Thus in relation to future climate targets, our quantification shows the *current* potential of ICT to contribute to these targets. This is thus a conservative route, as ICT methods for interfacing with households are likely to improve as may the overall energy efficiency of appliances [see e.g. 20, 46]. For every country the national energy mix factor of electricity production, available from Covenant of Mayors [69], was used for translating the energy savings into reductions in CO_2e emissions.

Table 2 shows our quantification strategy and the results for the estimation based on all the “middle value” parameters that are presented in Table 1. We interpret the results of the CO_2e abatement potential from ICT from the quantitative analysis in relation to the total required emissions reductions needed to keep global warming below 1.5 °C. Specifically the IPCC estimates that humankind will need to reduce GHG emissions by 70–95% by 2050 in order to hit this climate target [4, p 21]. For the EU to do its part in hitting this target it will need to succeed in reducing GHG emissions by a similar amount, which is reflected in the SET Plan goal of an 80% reductions in GHG emissions from the energy sector by 2050 [10]. Annual total emissions in the EU-28 are 4451.8 mio. tCO_2e (million tons of CO_2 equivalent) according to 2015 Eurostat data. Emissions were at 5700 mio. tCO_2e in 1990, showing the EU's success at reducing emissions over this time period. In 2015, about 55% of EU-28 emissions were related to the energy sector, which amounts to 2448.6 mio. tCO_2e emitted by the energy sector in this year. Taking this figure as the baseline, the targeted reductions by 2050 are 80% of 2448.6 mio. tCO_2e or 1958.4 mio. tCO_2e annual abatement from the energy sector.

Looking first at the results of the country-wise quantification in Table 2 we see heterogeneity across EU-28 nations in terms of the per household quantity of CO_2e emissions that are able to be abated due to ICT-based household interventions. This heterogeneity is driven exclusively by the differing electricity consumption and emission factors in each nations, where a higher emission factor indicates more CO_2e intensity in electricity production, as the parameter values relating ICT to household energy decisions are the same across nations. Thus, nations with higher per household energy usage and/or higher emissions factors are able to abate more emissions through ICT.

We have aggregated the data shown in Table 2 across EU-28 nations for indicators of interest, and then repeated the process for the ranges of parameter values shown in Table 1, namely the “optimistic” and “pessimistic” sets of parameter values. The aggregated results are shown in Table 3. We see from Table 3 that the total potential contribution of ICT-based interventions on household electricity usage to CO_2e reduction across the EU-28 is in the range of 4.5–64.7 mio. tCO_2e per year, with a middle estimate of 24.9. This represents 0.23–3.3% of the EU target of CO_2e reduction from the energy sector to keep warming under 1.5 °C. The percent of this target from the middle estimate is 1.22%, which is again based off a reductions target of 1958.4 mio. tCO_2e not emitted from the energy sector.

Using the EU as a leading case, we can then generalize our quantification to the global level. Global anthropogenic GHG emissions were about 49 $GtCO_2e$ (gigatonnes CO_2 equivalent) per year and about 25% of this comes from the energy sector [4]. Taking an emission reduction of 80% by 2050 as the target to reach the 1.5 °C warming goal implies that the global energy sector needs to reduce GHG emissions by 9.8 $GtCO_2e$. Extrapolating the potential effect of ICT found for the EU globally, suggests that ICT-based interventions in household electricity use could reduce annual CO_2e emissions by 0.023–0.32 $GtCO_2e$

[4] Statista [67] estimates a penetration rate of smart home systems in Europe of 5.2% in 2017.

Table 2
Country-specific calculation of per household CO2-reduction potential from ICT-based effects on electricity consumption.

Country	Electricity consumption per household [in kWh/a]	Emission factor for consumed electricity[a] [kg CO_2e/kWh]	Electricity saved per household due to behavioural changes [in kWh/a]	Electricity saved per household due to efficient appliances [in kWh/a]	Electricity load shifted to off-peak times [in kWh/a]	CO_2e reduced by behavioural change and appliances [kg CO_2e/a]	CO_2e reduced by loadshift [kg CO_2e/a]	Total [kg CO_2e/a]
Austria	4548	0.31	90.95	112.55	454.76	63.09	14.10	77.18
Belgium	3874	0.40	77.47	95.87	387.35	69.68	15.57	85.25
Bulgaria	3672	0.91	73.45	90.89	367.25	148.89	33.27	182.17
Cyprus	4769	1.02	95.37	118.03	476.87	217.45	48.59	266.05
CZ	3283	0.80	65.67	81.26	328.34	117.84	26.33	144.17
Denmark	3617	0.76	72.34	89.53	361.72	123.02	27.49	150.51
Estonia	2890	1.59	57.79	71.52	288.95	205.98	46.03	252.01
Finland	7674	0.42	153.48	189.93	767.40	143.55	32.08	175.62
France	5081	0.15	101.63	125.77	508.15	33.20	7.42	40.62
Germany	3187	0.71	63.74	78.88	318.69	100.69	22.50	123.19
Greece	4173	1.17	83.46	103.28	417.31	217.93	48.70	266.63
Hungary	2524	0.68	50.48	62.47	252.40	76.58	17.11	93.69
Ireland	4620	0.87	92.40	114.34	462.00	179.87	40.19	220.06
Italy	2613	0.71	52.27	64.68	261.34	82.80	18.50	101.30
Latvia	2109	0.56	42.17	52.19	210.86	53.12	11.87	65.00
Lithuania	2078	0.17	41.57	51.44	207.83	16.18	3.62	19.80
Luxembourg	4321	0.79	86.43	106.95	432.13	152.77	34.14	186.91
Malta	4009	0.70	80.18	99.23	400.91	125.59	28.06	153.65
Netherlands	4548	0.72	90.96	112.56	454.80	145.72	32.56	178.29
Poland	2083	1.19	41.66	51.55	208.28	110.45	24.68	135.13
Portugal	2871	0.75	57.42	71.05	287.09	96.35	21.53	117.89
Romania	1637	1.08	32.74	40.52	163.72	79.42	17.75	97.16
Slovakia	2603	0.35	52.06	64.42	260.29	41.12	9.19	50.30
Slovenia	3888	0.60	77.76	96.22	388.78	104.74	23.40	128.14
Spain	3765	0.64	75.31	93.19	376.54	107.67	24.06	131.73
Sweden	8914	0.08	178.28	220.62	891.39	31.51	7.04	38.55
UK	3852	0.66	77.03	95.33	385.16	113.41	25.34	138.76
AVERAGE	3822	0.70	76.45	94.60	382.23	109.58	24.49	134.07

[a] The emissions factors for Malta and Luxembourg are based on their country specific energy efficiency reports from 2011.

Table 3
Total potential effects of ICT on household electricity use across the EU-28.

Parameter values	Total electricity shifted to off peak times [in TWh/a]	Total Electricity Saved [in TWh/a]	Total emission reduction [mio. tonnes CO_2e/a]
Middle Values	80.15	35.87	24.94
Optimistic Values	136.25	79.75	64.69
Pessimistic Values	40.07	8.01	4.56

Parameter values defined in Table 1.

(23–320 mio. tCO_2e). This extrapolation is based on the assumptions that: ICT-based interventions have similar efficacy to what has been shown in the EU across the globe, that these interventions are spread to all households, and that ICT and energy efficiency technology level remains constant.

5. Conclusion

This paper investigates the potential for ICT-based interventions to decrease energy usage and improve energy efficiency in households. The behavioural literature on the subject, summarized in Section 2, suggests that ICT can affect two main behaviour-influencing factors, motivating and reinforcing factors, and discusses the causal avenues for this effect to take hold. In Section 3, we synthesize the literature that has estimated the magnitude of the effect of ICT on various aspects of household energy behaviour. The findings of past literature are used to define parameter values, which reflect the efficacy of ICT at changing household energy usage patterns, and ultimately decreasing CO_2e emissions from the electricity sector. Utilizing the range of parameter values, we complete a quantitative analysis of the potential for ICT to contribute to reaching the 1.5 °C target in the context of the EU energy sector. The EU case is generalized to the World's economy based on various assumptions. We find that ICT could contribute between 0.23% and 3.3% of the EU CO_2e reduction target from the energy sector that would keep warming under 1.5 °C. This corresponds to 4.5–64.7 mio. tCO_2e abated per year, with a middle estimate of 24.9, in the EU case, and 23–320 mio. tCO_2e, with a middle estimate of 120, in the global case.

This quantification reveals the potential impact of ICT-based interventions in households to mitigate CO_2 emissions from the electricity sector. While the overall effect of ICT is a not large relative to the total CO_2 reductions necessary to meet the 1.5 °C target, the total potential reduction in the quantity of CO_2e emitted by the energy sector is significant. Thus, ICT can clearly add value to the effort at energy system de-carbonization as a part of an “all of the above” transition strategy. In particular, we find that the CO_2e reduction potential of ICT interventions that bring about behavioural change and energy efficiency in household appliances could have a significant effect on CO_2e emissions from the electricity sector. However, ICT interventions related to loadshifting and demand response should not be discounted as they can enable more renewable generation sources to be tied to the grid, even if their estimated direct impact on CO_2 reduction is low.

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Conflict of interest

The authors declare that they have no conflict of interest.

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